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GENESIS OF THE ALKALINE ROCKS

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## INTRODUCTION

The eruptive sequence in the compact and quite isolated igneous complex at Ascutney Mountain, Vermont, opens with gabbro and closes with dike rocks, including its chemical equivalent, diabase. The gabbro seems locally to merge into a type intermediate between essexite and a basic diorite. That body is cut by dikes of a mafic rock which shares the characteristics of monzonite and ideal essexite.<sup>1</sup> Intruding the gabbro, "diorite," and essexitic monzonite are several stocks or thick dikes of alkali-rich syenites, themselves cut by a stock of alkaline granite. Still younger are the diabase dikes.

The study of Ascutney Mountain, begun in 1893, introduced the writer to the problem of the so-called alkaline rocks. There he first became skeptical of the dogma that the alkali-rich magmas have originated independently of the subalkaline (lime-alkali)

<sup>1</sup> The relation between this micropertite-orthoclase-plagioclase rock and the gabbro-"diorite" body, described in *Bull. 209, U.S. Geol. Surv.*, 1903, was proved in 1916.

magmas. That doubt was confirmed during observations in the volcanic fields of France, Italy, and Germany, in the colossal igneous fields of the North American Cordillera, and in Hawaii.

North of the Hawaiian volcano, Hualalai, soda-rich trachyte rests on, and is surrounded by, great flows of olivine basalt. This spectacular association could not fail to recall the problem which had been so baffling during the interval of sixteen years. More than ever the writer was convinced of the extreme intimacy of the alkaline and subalkaline suites of igneous rocks. The relatively small volume of all known alkaline rock and the small absolute sizes of alkaline bodies had suggested their derivation from the overwhelming subalkaline magmas, but it was not until the Hawaiian lavas were closely considered that a promising clue to an explanation was found.

The hypothesis involving that clue was published in 1910. One outstanding fact on which the hypothesis is based is the common occurrence of feldspathoids in the alkaline rocks instead of, or alongside, feldspars, which are the dominant constituents of the subalkaline rocks. The presence of nephelite or leucite signifies a lack of silica available for full saturation of soda or potash or both, suggesting some desilication of original subalkaline magma. Secondly, the concentration of alkalis in many alkaline rocks means that some agent or group of agents had collected the alkalis from the original magma. No success characterized the attempt to imagine adequate causes for the desilication or for the enrichment in alkalis, if the magma remained throughout purely juvenile in origin. The writer was thus led to assume the absorption of foreign material as the responsible condition. Such material is basic sedimentary rock. The most basic, large-scale, and widely spread rocks are limestone and dolomite. Also on account of the relative chemical simplicity of the carbonates the writer laid stress on these particular sediments. Unfortunately certain authors have thought that it was intended to explain all alkaline rocks by the interaction of resurgent carbonates with subalkaline magma, though that was disclaimed in the original paper.<sup>1</sup> In 1913 the hypothesis was elaborated and the very important case of the

<sup>1</sup> *Bull. Geol. Soc. Am.*, XXI (1910), 108, 113, 114, 116.

syenites was speculatively treated. For those rocks, the most voluminous of the whole alkaline suite, *hydrous, basic* sediments (with or without calcareous associates) were considered as the probable agents of desilication and concentration of alkalis.<sup>1</sup> Thus, while the absorption of small amounts of limestone or dolomite seems to be the chief cause for the differentiation of most nephelitic and leucitic rocks, many other alkaline types were explained by the assimilation of hydrous sediments, in indefinitely varied mixture with one another or with more siliceous rocks or with carbonate rocks.

During the last four years new field observations and some experimental work bearing on the subject have been reported, and important papers on general theory as well as on special points have been published. A review of these matters and correlated observations of older date is the purpose of the present article. A full discussion of the origin of alkaline rocks is not attempted, but rather a supplement to corresponding chapters in the writer's *Igneous Rocks and Their Origin*. After brief discussion of the field and chemical studies, Bowen's petrogenic theory, the strength of which is so largely measured by its ability to explain the alkaline rocks, will be analyzed in some detail.

#### RECENT FIELD OBSERVATIONS

Many investigators of alkaline rocks still continue to give merely petrographical descriptions. Others discuss the origin of the rocks, but are content to refer the various types to differentiation without giving any adequate idea of what was differentiated. A few writers during the last four years have more seriously considered the questions of origin, and it is worth while to note their findings.

*Relation of the alkaline and subalkaline suites.*—From new localities have come proofs of the exceedingly close time and space associations of the alkaline ("Atlantic") and subalkaline ("Pacific") eruptives. Among those who have lately laid emphasis on the point are Lacroix, Smyth, Cross, Washington, Holmes, Bowen, Harker, and the writer.<sup>2</sup>

<sup>1</sup> R. A. Daly, *Igneous Rocks and Their Origin* (New York, 1914), p. 395.

<sup>2</sup> A. Lacroix, *Bull. soc. géol. France*, X (1910), 91; *Comptes rendus*, CLV (1913), 538; C. H. Smyth, *Amer. Jour. Sci.*, XXXVI (1913), 41; W. Cross, *Prof. Paper 88*, U.S. Geol. Surv., 1915, pp. 85, 91; H. S. Washington, *Compte rendu, Cong. géol. internat.*

The cited paper by Washington is worthy of special mention. He is certainly right in pointing out the vague nature of the expression "alkaline suite." The recognized difficulty of assigning some rocks to it rather than to the subalkaline suite matches the perfect transition between the two series. The use of these names involves danger to correct thinking if, while using them, the petrologist does not resist the idea that the two distinct suites really existed as such from the earth's beginning. Nevertheless some general name for alkali-rich rocks and their syngenetic associates is useful, and "alkaline" will be here so employed.

An illustration of the bond between the two suites is seen in the relation of albite-rich or oligoclase-rich lavas, the so-called spilites, to normal basalt, dolerite, or diabase.<sup>1</sup> Sargent has just proposed the term "auto-metamorphism," symbolizing his conclusion that the Lower Carboniferous spilites of Derbyshire have been derived from common basaltic magma through the "retention of volatile constituents resulting from the physical environment of a submarine flow."<sup>2</sup>

Though a follower of Becke in his interpretation of the "Atlantic" and "Pacific" suites, Winkler sees the intimacy of the two in the Eastern Alps (Steiermark). There the Pliocene was a time of extrusion of "Atlantic" magma, from which nephelite regularly crystallized. Winkler explains contemporaneous rock types more characteristic of the "Pacific" suite (normal basalts) by silication due to the solution of quartzose sediments in the original "Atlantic" magma.<sup>3</sup>

*Ice River intrusion, British Columbia.*—Allan states that the Ice River intrusive furnishes "a very strong case in favour" of the sediment-syntectic hypothesis (desilication) as applied to nephelite syenites and their allies—an explanation squarely opposed to that

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(Ottawa, 1914), p. 235; A. Holmes, *Mineral. Mag.*, XVIII (1916), 71; N. L. Bowen, *Jour. Geol., Suppl.*, XXIII (1915), 59; *ibid.*, XXV, 220; A. Harker, *Jour. Geol.*, XXIV (1916), 556; R. A. Daly, *Bull. Geol. Soc. Am.*, XXVII (1916), 329.

<sup>1</sup> Cf. S. von Szentpétery, *Mitt. Mineral. Geol. Sammlung des Siebenbürg. National-museums, Kolozsvár*, Band I, No. 2, 1912.

<sup>2</sup> H. C. Sargent, *Nature*, XCIX (1917), 59; *Phil. Mag.*, XXXIII (1917), 535.

<sup>3</sup> A. Winkler, *Zeit. für Vulkanologie*, I (1914), 182.

given by Winkler for the Alpine rocks just mentioned. In order to reach its present position the magmatic material at Ice River "had to travel through at least 10,000 feet of limestone or highly calcareous sediments of Cambrian age, and 3,000 feet of more or less calcareous shales."<sup>1</sup> Allan also finds evidence of resurgent carbon dioxide, volatilization of the alkalis, and gravitative adjustment in this remarkable complex. Large xenoliths of shale and limestone show plainly (p. 190) the introduction of alkaline solutions, which have caused in the xenoliths the crystallization of feldspars, nephelite, sodalite, and cancrinite, along with many lime minerals.<sup>2</sup>

*Haliburton County, Ontario.*—Foye has made a very important contribution to the subject as a result of his study of the nephelite syenites and adjacent formations in Haliburton County, Ontario.<sup>3</sup> Adams and Barlow had proved a large part of the associated amphibolites and pyroxenites to be due to the contact metamorphism of thick limestones by numerous granitic sills and "batholiths" (these described by Foye as laccoliths).<sup>4</sup> Foye was able to show that the magmatic emanations so largely responsible for this profound metamorphism were very like the material that went to form the nephelite syenite of the region. The total volume of the amphibolites thus formed is many times greater than the total volume of the nephelite syenite, making all the more probable the view that this alkaline rock has been formed pneumatolytically. Foye goes farther and concludes that the gases engaged in segregating the alkalis included resurgent carbon dioxide (and water), derived from the limestones and other interbedded sediments as these reacted with the granitic magma. Granite injections and limestones together made a "gigantic steam pack," from which alkaline volatile matter was expelled. Part of this formed a large proportion of the amphibolite; a much smaller part was trapped

<sup>1</sup> J. A. Allan, *Memoir 55, Geol. Surv. Can.*, 1914, p. 211.

<sup>2</sup> Compare the nephelitic schliers and nephelite-lined vugs in the nephelite basalt of the "Löbauer Berg," described by J. Stock, *Tschermaks Min. und Petr. Mitt.*, IX (1888), 438.

<sup>3</sup> W. G. Foye, *Amer. Jour. Sci.*, XL (1915), 413.

<sup>4</sup> W. G. Foye, *Jour. Geol.*, XXIV (1916), 783.

in the sill and laccolith chambers and finally crystallized as nephelite syenite and its by-products.

The crescentic laccolith near Tory Hill illustrates gravitative differentiation, also well displayed in several other of the thicker alkaline bodies. The maximum thickness of the laccolith is only about three hundred feet, yet it shows a striking variation from top to bottom as here indicated:

a) Pegmatitic nephelite syenite, with specific gravity of 2.674; carries micropertthite (59 per cent), nephelite (21 per cent), and albite (12 per cent); contacts with limestone roof.

b) Monmouthite, with specific gravity of 2.719; carries nephelite (57 per cent), albite (9 per cent), scapolite (10 per cent), and biotite (22 per cent).

c) Hornblende-nephelite rock, with specific gravity of 3.124; carries nephelite (30 per cent), albite (7 per cent), pyroxene (20 per cent), hornblende (30 per cent), garnet (7 per cent), and primary calcite (5 per cent).

d) Garnet-pyroxene rock, with specific gravity of 3.383; carries albite (3 per cent), pyroxene (34 per cent), garnet (37 per cent), and primary calcite (25 per cent); contacts with limestone floor.

The mineralogical composition of the Tory Hill and other laccoliths of the district directly indicates the probability of syntaxis between magma and limestone. Of course there is no necessity of assuming that all, or even the larger part, of this assimilation took place at the visible contacts.

*Palingenesis in relation to the problem.*—Basaltic magma may not at all have participated in these Ontario developments. The writer suspects that, like many other pre-Cambrian invasions of magma, the petrogenic cycle was not opened by the abyssal injection of basalt. Along with Lawson, Sederholm, and other workers in pre-Cambrian complexes, one is rather tempted to regard the activity of the granite magma as due to palingenesis, that is, refusion of the crustal granite at a level not far below that to which erosion has brought the general surface of Haliburton County. This whole field exemplifies the difficulty of applying to the granites of the older pre-Cambrian terranes any petrogenic scheme that



may succeed in explaining post-Cambrian eruptive bodies and sequences.

*Azof region, Russia.*—Guinsberg believes that the limestone-syntectic hypothesis is valid for the nephelitic and other alkaline rocks studied by him in the Azof (Mariupol) region, even though they do not make visible contact with limestones at all. He

explains the origin of the nephelite-syenite by the mixture of a basalt-magma with limestone followed by a differentiation in alkali rocks and pyroxenite. Although the limestones were not discovered in this district, the presence of sedimentary rocks such as quartzite was established. In the neighboring district of Berdjansk, which forms the continuation of the same crystalline area, Morozewicz found among the crystalline schists together with quartzites also limestone and graphitic gneiss.<sup>1</sup>

*Reinhardswald, Germany.*—Apel's recent work on the Reinhardswald district of Northern Germany gives the petrography of a large number of volcanic necks.<sup>2</sup> The eruptives include: common basalt, dolerite, enstatite dolerite, trachydolerite, nephelite basalt, melilite-bearing nephelite basalt, leucite basalt, leucite basanite, limburgite, and nosean-bearing limburgite. Other types represent the transition between nephelite basalt and leucite basalt.

This assemblage claims notice as another example of the close connection between alkaline varieties and feldspar basalt. Lepsius' geological map of Germany seems to show that the alkaline-lava vents are here largely or wholly confined to areas underlain by the Muschelkalk at the time when the volcanoes were active, numerous vents filled with feldspar basalt and dolerite appearing specially in Bunter Sandstein areas. The writer has not been able to check this generalization by reference to a large-scale geological map of the region, but has thought the question involved might well be put on record. In any case the possible chemical influence of the Muschelkalk on the magmas which fluxed, stoped, or exploded their way to the earth's surface needs investigation. The problem is complicated on account of the partial removal of the limestone by erosion since the volcanic epoch.

<sup>1</sup> A. Guinsberg, "Pierre le Grand à Pétrograde," *Annales de l'Inst. Polytech.*, XXV (1916), 435.

<sup>2</sup> K. Apel, *Neu. Jahr. für Mineralogie*, etc., B.B. XXXVIII (1914), 525.

*Almunge, Sweden.*—Among the most noteworthy publications of late years is Quensel's paper on the alkaline rocks of Almunge.<sup>1</sup> Consisting of dominant umptekite with an aplitic marginal zone and with huge inclusions of canadite (albite-nephelite syenite), these rocks form a stocklike body measuring 4.5 by 3.5 km. It cuts granite of two types. Quensel's memoir is full of valuable information, but two chief points are of present importance. One is the abundance of the two lime minerals, vesuvianite and primary cancrinite, in the canadite. The other is Quensel's suggestion as to the genesis of this rock. His statement may be quoted (p. 196):

Vesuvianite has always been considered a typical mineral of the contact metamorphism of calcareous rocks. It seems difficult to explain its presence in the Almunge canadites in any other way than that it represents the remains of otherwise fully assimilated calcareous sediments. Its occurrence would then be comparable with the primary calcite of Alnö or Bancroft, formed through assimilation of limestones by the igneous magma under such circumstances that the CO<sub>2</sub> could not abscond. The very essential amount of cancrinite in all these rocks would then probably be a manifestation of the same geological features. The presence of a hydrated mineral in an igneous rock is hardly more remarkable than CO<sub>2</sub> partaking in the constitution of other magmatic minerals under similar circumstances.

Though nothing can be said with certainty about the origin of the alkaline rocks, several features seem, however, to point to the possibility of the origin of nepheline-syenites in some way having been connected with the assimilation of calcareous sediments. As previously mentioned, paragneisses with interbedded limestone are found at no very great distance south of the area and may possibly be present at deeper levels within the Almunge district itself.

The writer is free to admit that future field work at a number of other localities is not likely to yield results positively favorable to the sediment-syntectic hypothesis for the alkaline rocks. Yet the

<sup>1</sup> P. D. Quensel, *Bull. Geol. Inst. Upsala*, XXII (1914), 129. While the proofs of the present paper were being read, Thorolf Vogt's account of the rocks of Hortavaer, Norway, reached America [Videnskapsselskapets Skrifter, I Mat.-naturv. Klasse, Christiania (1915), No. 8]. Vogt describes the peripheral solution of large limestone masses in intrusive subalkaline magma, with the resulting generation of alkaline pyroxenes which chiefly compose "hortite," a new plutonic type. He concludes that the injection temperatures were in the neighborhood of 1300° C. for the intrusives at Hortavaer and at Alnö, Sweden! Still other features of Vogt's paper are significant in connection with the sediment-syntectic hypothesis, which he regards as sound at least in part, but space fails for a fuller discussion of this careful petrological study.

apparent or real absence of basic sediments at those places is not immediately compelling to anyone who remembers the complex conditions due to deep erosion, to inadequate exposures, to "staccato" injection,<sup>1</sup> to the lateral migration of magmas, as proved in the case of sill or laccolith, and to the probable fact that most pre-Cambrian granite (and orthogneiss) has been concordantly injected and may therefore in a given instance cover thick, basic sediments not locally exposed. The last-mentioned principle affects the negative evidence for appropriate country rocks around the alkaline eruptives of the Julianehaab district, the Kola Peninsula, Cripple Creek, certain localities in New Hampshire and East Africa, etc.

The repeated objection that some granites, granodiorites, and other subalkaline bodies cut limestones and yet do not show obvious chemical reaction with the sediments is not necessarily valid. Such contacts may simply indicate the respective magmatic temperatures to have been too low for the reaction. Before stopping or other mechanical movements had established any of these contacts the temperature may have been higher, so that solution of limestone was then possible. However, unless the limestone made a considerable part of the whole rock mass dissolved (otherwise likely to be composed of siliceous country rock), the effects of the solution of limestone might be masked by the differentiation of each great body of magma. In a special case a batholith may have stopped its way to the limestone just as the dissolving power of the magma was approaching zero.

*Hawaii.*—Cross's valuable memoir on the Hawaiian lavas bears the conclusion that the alkali-rich rocks and melilitic rocks of the archipelago are "products of the same general process of differentiation [of original basalt] as the other rocks with which they are associated."<sup>2</sup> He rejects the sediment-syntectic hypothesis, partly because he doubts that limestones are "associated with the older lavas of the archipelago." He fails also to see how "superficial deposits of coral limestone . . . can gain access to the volcanic conduit in mass sufficient to produce any notable result." Yet

<sup>1</sup> Cf. R. A. Daly, *Amer. Jour. Sci.*, XLIII (1917), 444.

<sup>2</sup> W. Cross, *op. cit.*, p. 90.

thick limestones do underlie the lavas of Oahu, and it is scarcely credible that during the slow growth of the volcanic piles through 2,500 fathoms of warm Pacific water there should be no interbedding of calcareous oozes, coarser shell deposits, or coralliferous limestones. The magma of a volcanic vent, locally fluxed through such a composite, could not fail to incorporate some calcareous material. The remaining question is as to how much assimilation is "sufficient to produce any notable result." The answer is—comparatively little. Since alkali-rich rocks are very rare in Hawaii and, so far as known, of small individual volumes, the absolute amount of limestone assimilation need be very slight and in any case quite local.

The syntexis of basalt and limestone is positively suggested by the several occurrences of nephelite-melilite basalt in and around Honolulu, where deep borings have proved the existence of thick limestones which must have been traversed by the conduits of these lavas. In the same region are nephelite basalts. As Cross states, it may be "certainly true that the alkali-rich lavas are not present about Honolulu," but the first step in limestone syntexis is obviously not an alkali-rich magma. That can originate only under conditions allowing drastic differentiation. According to the present writer's view, the flows of melilitic and nephelitic basalts are quenched phases, erupted before much concentration of alkalies in the vent was possible. As Bowen agrees, melilite is possibly a direct sign of syntexis with limestone rather than of pronounced differentiation. Ten years ago Becker published the hypothesis that the melilite in the basalts of the Wartenberg and of Southwest Germany in general have resulted from the absorption of calcareous sediments.<sup>1</sup>

*Tahiti*.—Marshall, by actual field work, has well supplemented Lacroix's petrographic studies in Tahiti.<sup>2</sup> In the central pipe of the island he found an alkali-rich syenite associated with wehrnite and gabbro. This stocklike or necklike body traverses the flows

<sup>1</sup> Cf. N. L. Bowen, *op. cit.*, Suppl., XXIII (1915), 89; R. A. Daly, *Igneous Rocks and Their Origin* (New York, 1914), p. 436; E. Becker, *Zeit. deut. geol. Gesell.*, Band LIX (1907), 273.

<sup>2</sup> P. Marshall, *Trans. New Zealand Inst.*, XLVII (1915), 361.

of dominant, common basalt. The syenite and other alkaline types have suggested the problem of origins to Marshall. He finds no evidence favoring the sediment-syntectic hypothesis in this case. A chief ground for doubting it is the assumed lack of limestone in the volcanic pile. Marshall admits that globigerina ooze veneers the submarine flanks of Tahiti, but implies that neither ooze, coralliferous limestone, algal limestone, nor shell limestone was interbedded with the basaltic flows during the slow submarine growth of the volcano. Again one must ask if such interbedding can, under the tropical conditions, possibly be doubted. Again, too, the required amount of assimilation of limestone and other sediments would be small.

*Queensland.*—Richards has published an excellent study of the Tertiary volcanic rocks of southeastern Queensland.<sup>1</sup> These are divisible into three stratigraphic divisions. The lowest is composed of common basalts. The middle division includes augite andesite, rhyolite, comendite, trachyte, soda-trachyte, phonolitic aegirite trachyte, and pantellerite. The upper division is dominantly basaltic, with flows of olivine basalt, olivine-free basalt, andesitic basalt, oligoclase basalt, and andesite. The alkaline rocks “constitute at the most 5 per cent of the volcanic material.” Richards regards all types as mere differentiates of a single original magma and follows the all too common plan of calculating its composition from the volumes and compositions of the visible rocks only. Inasmuch as no reckoning is made of the other magmatic phases that must have remained in the magma chambers below the earth’s surface, the estimate is entirely misleading and, for its purpose, of no immediate value.<sup>2</sup>

On account of the relatively small amount of limestone in the country rocks, Richards finds unsatisfactory the sediment-syntectic hypothesis in explanation of the Queensland alkalines. However, limestone is not necessarily a partner in a syntectic from which trachytes, pantellerites, or comendites are differentiates. The writer has indicated the grounds for regarding shales and other subsiliceous, hydrous sediments as more influential in the generation

<sup>1</sup> H. C. Richards, *Proc. Roy. Soc. Queensland*, XXVII (1916), 105.

<sup>2</sup> The same principle applies to alkaline provinces in general.

of trachytic and syenitic magmas generally.<sup>1</sup> The solution of small amounts of Mesozoic and Paleozoic non-calcareous sediments (or of their connate waters) in basaltic magma may be primarily responsible for the quite subordinate, alkali-rich lavas of Queensland. The traces of calcareous material in these sediments might co-operate in the underground reactions, but carbonates were not in chief control.<sup>2</sup>

#### SPECIAL CHEMICAL CONSIDERATIONS

“*Saturation*” in igneous rocks.—Shand expresses a suggestive idea in distinguishing “saturated,” “undersaturated,” and “oversaturated” igneous rocks.<sup>3</sup> Saturated rocks are those that contain only minerals which are capable of forming in the presence of free silica. Any rock containing free quartz or tridymite of magmatic origin is said to be oversaturated. Undersaturated rocks are composed, wholly or in part, of minerals unsaturated with silica. Shand’s list of unsaturated minerals includes leucite, nephelite, sodalite, nosean, analcite, cancrinite, hauyne, melanite, melilite, magnesian olivine, corundum, and perovskite—all characteristic components in alkaline rocks.<sup>4</sup>

One of the causes for undersaturation Shand finds in assimilation. He writes (p. 511):

When the invaded rock is a carbonate or other non-silicate rock, or contains much lime, magnesia, or iron in the form of oxide or carbonate, then the advantage as regards absorbing power lies with the saturated and oversaturated magmas, which can yield first their excess of silica, and secondly a further quantity of silica due to the reduction of sodium, potassium, calcium, and magnesium molecules from the saturated to the unsaturated state. In this way a saturated or oversaturated magma may become undersaturated.

<sup>1</sup> R. A. Daly, *Igneous Rocks and Their Origin* (New York, 1914), pp. 393, 410.

<sup>2</sup> The remark of Richards (p. 190), that “Dr. Jensen has also advocated the assimilation of carbonate rocks by the parent magma with the resultant production of alkaline material,” is hardly a correct rendering of Jensen’s hypothesis. Jensen assumes the precipitation of “alkaline salts” to the floor of the primitive ocean, their burial, and their later fusion and fluxing with the silicates of the overlying rocks. The present writer has not “elaborated this view,” as Richards states.

<sup>3</sup> S. J. Shand, *Geol. Mag.*, X (1913), 508.

<sup>4</sup> See J. Morozewicz, *Tschermaks Min. und Petr. Mitt.*, XVIII (1898), .224. A. Holmes (*loc. cit.*, p. 71) points out that the basalts associated with the alkaline lavas of East Africa are also undersaturated with silica.

He favors the view that this condition applies to many alkaline rocks.

Among the consequences of undersaturation, according to Shand (p. 510), is the tendency of foyaitic or phonolitic magmas to enter "into chemical combination with the silica of invaded rock masses. The reactions thereby induced would be exothermic, and would tend to raise the temperature of the magma. . . . The access of heat produced in this way would in turn enable the magma to perform a further amount of work in the way of mechanical solution." One is reminded of Ramsay's conclusion that the umptekite of the Kola Peninsula is probably due to syntaxis between nephelite-syenite magma and siliceous sediments.<sup>1</sup> An analogy is found in Ussing's explanation of important masses of quartz syenite and soda granite in the Julianehaab district as products of reaction between augite-syenite magma and sandstone. Quensel, too, assumes syntaxis between the umptekitic magma of Almunge and older granite, giving the observed transition between the corresponding formations.<sup>2</sup>

Shand notes the relative insignificance of alkaline rocks in volume; the dominance of oversaturated rocks among major intrusions; the dominance of saturated and undersaturated rocks (including basalts) among lavas and minor intrusions; and (p. 512) the

strong suggestion that undersaturation may be characteristic of the deeper zones of the lithosphere, as oversaturation is of the higher. . . . Those igneous rocks which have been brought up most rapidly from the earth's interior, and have solidified most rapidly in or on the crust, are to a marked extent undersaturated. Those which have slowly worked their way up into the crust (and have hence had abundant opportunity for absorbing silica) are found to be predominantly oversaturated.

Comparison may be made with the idea of granitic, continental maculae overlying a basaltic earth-shell.

<sup>1</sup> W. Ramsay, *Fennia*, XI, No. 2 (1894), pp. 74, 95. As above noted, Winkler has given proofs of the solution of quartz in basic Alpine lavas which he considers as belonging in the alkaline suite.

<sup>2</sup> N. V. Ussing, *Meddelelser om Grönland*, XXXVIII (1911), 59, 191, 197, 363, 366; P. D. Quensel, *op. cit.*, XII (1914), 196.

*Action of "mineralizers" and of normal faulting.*—Cross, Bowen, Foye, and others approve Smyth's reference<sup>1</sup> of the alkali-rich rocks to the work of gases or "mineralizers" operating in subalkaline magmas. The pneumatolytic origin of many nephelitic, sodalitic, and cancrinitic rocks has indeed long been clear to the French and other intelligent students of their mineralogy and texture. The next important questions are as to the origin of the gases and the cause of the concentration of the gases. Smyth regards the gases as (p. 45) "magmatic or 'juvenile' rather than resurgent" and joins Harker in thinking that their concentration along with the alkalies probably depends on crustal dislocation by radial movements in the earth.

He makes no other suggestion as to the reason why the mineralizers should, in general, not have the power to develop nephelite syenites and similarly undersaturated rocks in most plutonic complexes. Water and other mineralizers form tremendous emanations in andesitic volcanoes, yet many of these lack phonolitic, trachytic, or other alkali-rich lavas. The present writer has shown that many alkaline bodies occur in zones of intense tangential compression, while, on the other hand, subalkaline bodies are abundant in areas of radial dislocation. The statistics of distribution are far from supporting Harker's thesis. It suffers also from the improbability of another underlying assumption—that in every instance the parent subalkaline magma was nearly frozen at localities where normal faulting has caused the eruption of multitudes of small alkaline masses. The mechanism is seen to be one of almost infinite delicacy and hence of doubtful reality, at least on the scale demanded. One may observe also that normal faulting need not exert a notable squeezing-out effect if the magma chamber were not cut by the fault planes. A semiliquid mass inclosed in a down-thrown or upthrown block would not necessarily undergo any differential stress. The alternation of liquid basalt and trachyte or phonolite at the same volcanic center is one of the more obvious difficulties with the speculation.

Further, the Harker hypothesis does not take proper account of the lamprophyres which usually close petrogenic cycles. While

<sup>1</sup> C. H. Smyth, *op. cit.*, p. 33.



aprites are explained, vogesites, spessartites, and odinites are not. If tinguaites or nephelite pegmatites represent residual liquids, what is the meaning of the camptonites or alnöites, so closely associated both in time and space with those alkaline types? In some nephelite-syenite areas camptonites not only are abundant but appear to be even younger than most of the tinguaites. There is manifest trouble in explaining *both* the salic and femic dike groups as crystallizations from residual liquid.<sup>1</sup>

Considering the weakness of the idea relating alkaline magmas to crustal dislocation of a special kind, Smyth's conception needs an important supplement. It would be strengthened if a more probable cause for the local, quite exceptional, concentration of the mineralizers and alkalis in purely juvenile magma were discovered. This has not yet been done. On the other hand, the local assimilation of sediments cannot, in general, fail to enrich subalkaline magmas in gaseous constituents, with the effect of segregating the alkalis, as the writer has long held.<sup>2</sup> In short, the combination of juvenile and resurgent "mineralizers" is believed to be a much

<sup>1</sup> A. Harker (*op. cit.*, p. 558) recently published a very doubtful argument in support of his contention that subalkaline ("calcic") rocks rather than alkaline rocks are genetically associated with "regions subjected to powerful lateral thrust." He writes: "If we examine those crystalline schists which are admittedly of igneous origin, together with foliated igneous gneisses, we find that they belong almost exclusively to the calcic branch. . . . Alkaline crystalline schists as a whole are quite insignificant as compared with any single type in the calcic division. . . . The striking disparity here noted is only one consideration among others which points to a peculiar distribution of alkaline and calcic igneous rocks in relation to crustal stresses."

Evidently the dynamic metamorphism in most of the cases cited followed *after* the respective eruptions. Some of the intervals between eruption and shearing have been proved to equal several geological periods. Can one assume that the resulting schistosity of the igneous bodies has any connection whatever with the generation of their magmas? Moreover, there is much to be said for the view that the schistosity and foliation of pre-Cambrian rocks largely originated during static metamorphism rather than during the operation of lateral thrust. It may be observed that neither great volumes nor wide distribution for the alkali-rich rocks would be expected in the older pre-Cambrian terranes by an upholder of the sediment-syntectic explanation of alkaline rocks.

<sup>2</sup> From the composition of the amygdale minerals in the alkaline lavas of Mozambique, A. Holmes (*Nature*, XCVIII [1916], 162) believes the corresponding magmas to have been rich in carbon dioxide as well as undersaturated in silica. The same author describes calcite inclusions in the analcite and nephelite of nephelinite at the Lucalla River, Angola, West Africa (*Miner. Mag.*, XVIII [1916], 64).

more likely cause than the action of the greatly overworked juvenile gases alone.

*Migration of free volatile materials from country rock.*—The addition of resurgent gas to a magma does not depend entirely on the solution of country rock as such. Elsewhere the writer has emphasized the high probability that connate water and other volatile substances in the country rock may be independently driven into injected magma.<sup>1</sup> An illustration is found in the so-called white traps of Scotland. Day holds that the otherwise typical basalt of the Cheese Bay sill has been reduced, whitened, and rendered vesicular by bituminous emanations from the intruded shale.<sup>2</sup>

*Relevant experiments.*—Controlled experiments on the chemical effects of dissolving limestone, dolomite, shale, etc., in subalkaline, particularly basaltic, melts are needed. They are sure to be difficult experiments if the conditions of nature are even approximated. Failing such direct tests, the information accruing from certain attempts to extract potash from feldspar commercially is not without value. According to Ross, if potash feldspar, lime (CaO), and water are heated together in a bomb at 300° C. and under a pressure of 91 atmospheres, the potassium is leached from the mineral and, as caustic potash, taken into the water solution. The amount of the leaching depends on the proportion of lime in the mixture until about three grams of lime are mixed with one gram of feldspar, when practically all of the potash is found to be leached.<sup>3</sup> In the same volume where Ross's paper appears (p. 646), R. J. Nestell and E. Anderson illustrate with actual analyses the strong volatilization of both potash and soda in the kilns of cement-mills. They agree with Ross in holding that the presence of lime tends to prevent a recombination of the alkalies with the silica of the original kiln charge.

Such experiments do not, of course, prove anything definite about magmatic reactions, but they do encourage the speculation that, in the presence of juvenile and resurgent water, carbon dioxide, and other volatiles, the alkali oxides may in a sense be

<sup>1</sup> R. A. Daly, *Amer. Jour. Sci.*, XLIII (1917), 445.

<sup>2</sup> T. C. Day, *Trans. Edin. Geol. Soc.*, X (1916), 249, 261.

<sup>3</sup> W. H. Ross, *Jour. Indust. and Eng. Chem.*, IX (1917), 467.

volatilized from a sedimentary syntectic and then concentrated either in the same magma chamber or in satellitic chambers. Whether the necessarily complex solutions will carry the alkalis free or as carbonates, aluminates, hydrates, silicates, or aluminosilicates is a problem not now to be solved, but it cannot fail to be considered by the serious student of the assimilation theory.<sup>1</sup>

Perhaps, too, experiment may yet tell the essential reason for leucitic (potash-rich) differentiates in one body and nephelitic (soda-rich) differentiates in another. Leucite, nephelite, and sodalite accompany such minerals as garnet, melilite, hauynite, and plagioclase in industrial slags. It would be of interest to know what contrasts of crystallization there may be in artificial melts, otherwise similar but with pure calcite as the only carbonate flux of the one group of melts and pure dolomite as the only carbonate in the other. Why is albite concentrated in spilite and orthoclase in the "orthoclase basalts"?<sup>2</sup> The reply, that each is due to differentiation, is hardly a reply at all. One needs to know what was the *cause* of each differentiation and *what it was* that differentiated.

#### BOWEN'S EXPLANATION OF THE ALKALINE ROCKS

*Summary of his general theory.*—Basing his results on an unmatched group of experiments, Bowen has given to the world a "systematic petrogenic theory" which is deeply concerned with the alkaline rocks.<sup>3</sup> Since the validity of his theory on this side depends on the general mechanism assumed, a considerable amount of attention must be given to main principles before the special reasoning applied by Bowen to the alkaline suite can be properly weighed.

His views may be summarized in his own words (pp. 89, 90): "Consideration of the factors limiting its scope has led to the decision that assimilation is, relatively speaking, an unimportant

<sup>1</sup> Compare G. W. Morey's thorough study of the ternary system,  $H_2O-K_2SiO_3-SiO_2$ , reported in the *Jour. Am. Chem. Soc.*, XXXIX (1917), 1173.

<sup>2</sup> S. H. Reynolds, *Quart. Jour. Geol. Soc.*, LXXII (1917), 23.

<sup>3</sup> N. L. Bowen, *Jour. Geol.*, Suppl., XXIII, 1915.

factor in the production of the diversity of igneous rocks." He agrees with "the great majority of petrologists" that

the rocks of any area vary among themselves in a systematic manner which indicates derivation from a common stock through some systematic process of differentiation from that stock.

The decision is reached that this differentiation is controlled entirely by crystallization. The sinking of crystals and the squeezing out of residual liquid are considered the all-important instruments of differentiation, and experimental evidence is adduced to show that under the action of these processes typical igneous-rock series would be formed from basaltic magma if it crystallized (cooled) slowly enough. The characteristic occurrence of basaltic magma as regional dikes and as the material of the great fissure eruptions is considered evidence of the primary nature of basaltic magma. It is concluded, therefore, that most, if not all, igneous rocks have probably been derived from basaltic magma, the processes of differentiation that have been pointed out above emphasizing the lighter, more salic and alkalic differentiates in the upper portions of very large, slowly cooled bodies.

*Definition of "differentiation."*—On page 3 of his paper Bowen defines differentiation as "any process whereby a magma, without foreign contamination, forms either a mass of rock that has different compositions in different parts or separate masses that differ from one another in composition." In two respects this definition is unsatisfactory.

The word "differentiation" is advisedly and very generally used to mean the actual separation of facies which were once in mutual solution or formed parts of the same body of erupted magma. One cannot postulate initial homogeneity for every erupted magma, nor assume that any heterogeneity a magma possesses has been caused by the break-up of an initially homogeneous solution. For example, if Suess's idea, that crust rocks are fused by juvenile gas rising from the deep, hot interior of the earth, should prove correct for any eruptive center, initial heterogeneity for the new magma would not be improbable. Each part of it might become still more heterogeneous through partial crystallization or other processes, but the original heterogeneity might persist. The rock phases resulting from originally different parts of the magma would be different; they can be called differentiates only by destroying the useful definition of "differentiation" already adopted, expressly or tacitly,

by most petrologists. A similar conclusion follows if any other cause for initial heterogeneity be considered.

Secondly, the term should apply to separations in hybrid magmas, whether formed by the mixture of two or more liquids (Bunsen, Harker) or by the magmatic solution of solid rock (Cotta, many French, Scandinavian, Russian, Australian, and Canadian petrologists). Bowen himself believes in a moderate amount of assimilation. As Loewinson-Lessing has specially insisted, a small degree of contamination with foreign material may change equilibrium in the magma, which therefore separates into strongly contrasted parts. It would be a pity, if it were possible, to exclude a change of the latter kind from the list of those properly covered by the name "differentiation."

Petrologists of the future are, indeed, likely to agree that this word shall be used to denote *separation* of phases and that its definition should be kept free from any presupposition as to the *origin* of the magma which does separate into parts, liquid or solid. Accordingly the units of differentiation may belong to one or more of the following six classes:

1. Contrasted fluid phases of an initially heterogeneous magma, including parts particularly rich in volatile constituents.
2. Solid crystals (fractional crystallization).
3. Mother-liquor left after partial crystallization.
4. Non-consolute liquid fractions (liquid immiscibility).
5. Material of fused country rock, not diffused into the original magma (ultra-metamorphism in part).
6. Original magma locally charged with material dissolved from the country rock, but slowly diffusing from the source of supply (syntexis).

Many field and laboratory observations suggest the control of gravity during the separation in any of the six cases. Given moderate viscosity for the magma, most early-formed crystals should rapidly sink. The formation of these crystals commonly means a decrease of density in the adjacent liquid, which is thus made specifically lighter than the surrounding magma. Such locally generated mother-liquor should tend to rise and concentrate near the roof of the magma chamber. Differential densities must tend

to cause gravitative adjustment among the liquid parts of an originally heterogeneous magma. The parts richest in gas are likely to rise roofward, displacing gas-poor parts of otherwise similar composition. A xenolith of gneiss, melted by, but not diffused into, a moderately viscous gabbroid magma, would rise rapidly and segregate with other melted bodies of the same kind. The most fusible part of the disintegrating xenolith would rise or sink independently. Even if diffused, the more acid foreign material locally lowers the density of the magma, for diffusion is a slow process. On the other hand, the local masses of acidified gabbro will rise quickly if the viscosity of the main body of gabbro is low.

Differentiation of the units described in classes 1, 5, and 6 may take place without any crystallization whatever; that is, all the phases concerned are liquid. Yet in none of the cases is the principle of fluid immiscibility necessarily concerned. The gas, juvenile or resurgent, like the xenolithic gneiss, may be perfectly miscible with the original magma; nevertheless gravitative adjustment is compelled long before homogeneity could be produced by the diffusion of foreign matter.

Whether true liquid immiscibility is an additional, perhaps very important, factor in magmatic differentiation is uncertain. Yet the repeated dogma that this question must be answered in the negative for natural silicate solutions is not warranted. The proper answer awaits the time when the influences of undercooling (by pressure, etc.) and volatile agents, as well as other unknown conditions, are better understood than now.

Bowen has done good service in confirming the view that the diversity of igneous rocks may be partly due to the sinking (or rising) of early-formed crystals in magma, but he has carried the principle farther than it is safe to carry it in the light of present knowledge and in the dark of present ignorance. His definition of differentiation is subjective, since that process is assumed to affect only purely juvenile magma "without foreign contamination." With respect to the biggest problem in petrogeny he thus takes a position which a host of field facts renders untenable. Certain observers ascribe to magma the power to dissolve completely large percentages of country rock. Others, more cautious

in admitting assimilation on the great scale, yet believe a small amount of syntexis to be capable of upsetting equilibrium in a primitive magma and so initiate its marked differentiation. These authors are so fortified with reasons for their faith that it is clearly expedient to keep an open mind concerning syntexis and to define "differentiation" accordingly.

*Absence of fractional crystallization in most basaltic sills.*—Another general objection to the pure-fractionation hypothesis is that it seems to prove too much. Numberless basaltic (diabasic, gabbroid) sills show by their wide extent that they were comparatively fluent during injection. Presumably the interior portion of each sill of notable thickness remained fluent for some time (hours, days, or weeks) after injection. During this interval the magnetite, olivine, augite, or calcic plagioclase of early crystallization would sink if the basalt regularly behaved like Bowen's crucible melts, on which he so largely bases his theory. Strong differentiation through the sinking of crystals was observed in his artificial melts after these had stood only a few minutes or at most a couple of hours. If, therefore, the experimental analogy were good, the average basaltic sill, five to fifty meters thick and hence slowly chilled, should exhibit differentiation by gravity. According to Bowen's argument, diorites or even quartzose phases might be regularly expected near the roofs and ultra-femic phases near the floors.

These deductions do not match the facts; the chemical homogeneity of most basaltic sills is almost perfect. The gravitative differentiation of basaltic magma is manifestly slow and, in a sense, difficult. Very thick sills, like that of the Palisades of New Jersey, may preserve magmatic life long enough for an appreciable sinking of specifically heavy crystals toward the bottom, but in general it looks as if some "contamination" were necessary before ordinary injected basalt breaks up into contrasted phases. The "contaminating" materials may be either exotic juvenile gas or resurgent gas or liquid.

*Comparative homogeneity of femic phases in differentiated sills and laccoliths.*—Where gravitative differentiation has taken place in sill or laccolith, the femic phase is commonly rather uniform from top to bottom, except at the layer transitional to the over-

lying, more salic phase. For example, the lower four-fifths of the Pigeon Point sill on the shore of Lake Superior is made up of gabbro. Locally the gabbro does bear interstitial micropegmatite, but from below upward there is no regular increase in this more siliceous ingredient. Such increase is rapid in the thin, overlying, intermediate rock, which is in turn overlain by the thicker, nearly homogeneous roof phase, micropegmatitic granite or red rock. According to the theory under discussion, the quartzose red rock represents the last surviving liquid of basaltic magma from which a correspondingly *large* crop of femic crystals had settled out. At some level between roof and floor these should be specially concentrated. Yet nowhere in the sill is there any important concentration of olivine, pyroxene, or iron oxides beyond the amounts characterizing a normal gabbro. The hypothetical ultra-femic phase is missing, despite the field evidence that the original magma was a rather typical gabbro.<sup>1</sup>

The same is true for at least some of the magnificent sills of the Purcell Mountains, also studied by the writer.

Incidentally, the cooling of a sill undergoing fractional crystallization is seen to be no simple matter. During the formation of a solid crystal, latent heat, estimated as about one-fifth of its total melting-heat, is given off. The fall of magmatic temperature at the level of its growth thus tends to be retarded. The deeper levels to which the crystal sinks share practically none of this latent heat in a direct way. Apart from other causes, the lower layers of the sill magma should therefore freeze first. The level of maximum aggregation of sunken crystals cannot be readily foretold, though it must be above the quickly chilled floor phase of the intrusive.

*Origin of the pre-Cambrian granites.*—Bowen considers all granite to be a differentiate of basaltic magma. Most of the continental surfaces are apparently underlain by pre-Cambrian complexes, chiefly of granitic composition, though so often metamorphosed to gneiss. If these stupendous masses of granite represent the silicic pole of separation in original basalt, most of the continents must now be underlain, still deeper than the granites, by solid rock much more femic than basalt and of great aggregate volume. Or

<sup>1</sup> Cf. R. A. Daly, *Amer. Jour. Sci.*, XLIII (1917), 423.



else the immense crops of olivine, pyroxene, magnetite, etc., were dissolved in still deeper, very hot magma which may still be liquid. If it is this magma that has been erupted in post-Cambrian time as basalt, then the original magma was not typically basaltic but more salic. On the other hand, there is no field evidence of the assumed generation of ultra-femic differentiates below the pre-Cambrian granite terranes, even if some special mechanism existed whereby the sunken crystals of this early differentiation were arrested at levels above the source or sources of the primitive basalt. Since peridotites, most probably derived from the relatively small volumes of basaltic magma involved in post-Cambrian igneous activity, have been erupted from time to time, it is reasonable to suppose that much more numerous and larger bodies of peridotites should have been erupted during the pre-Cambrian, if the pre-Cambrian granites were differentiated from basalt. The fact is that peridotites are by no means conspicuous in the pre-Cambrian complexes.

As noted elsewhere, the writer is more disposed to regard the basalt of the world as itself a primeval differentiate, the sunken part of an intermediate magma, of which the other risen part is the material now constituting the granitic terranes of the pre-Cambrian.<sup>1</sup>

*Rapid transitions between phases of differentiated injections.*— Though in each differentiated sill or laccolith the salic and femic phases are generally separated by a layer of rock chemically intermediate between the two, this layer is often very thin. Thus, at Square Butte, Montana, the transitional rock between the syenite and shonkinite of the well-known laccolith is only “a few inches or a foot or so” in thickness. Pirsson describes the transition as “extremely abrupt.”<sup>2</sup> Considering the large scale of this differentiation and remembering the distribution of the sunken crystals in Bowen’s experiments, such abruptness of transition is hardly to be expected if the differentiation were due merely to fractional

<sup>1</sup> From Bowen’s account of the evolution (p. 40) it is not easy to see how the potash of basalt could be concentrated in the proportion seen in granite, assumed to represent the residual liquid of an initially basaltic magma, unless the soda of the granite were much more abundant than the potash; yet in average granite potash dominates over soda.

<sup>2</sup> L. V. Pirsson, *Bull. 237, U.S. Geol. Surv.*, 1905, p. 51.

crystallization.<sup>1</sup> Nor here again does the hypothesis explain the comparative homogeneity of the shonkinite itself.

*Origin of quartz diabase.*—A difficulty is found also in the nature of that common sill rock, quartz diabase. Table I gives the average composition of twelve typical quartz diabases from various parts of the world (col. 1) and the average analysis of 198 fresh rocks of basaltic composition (col. 2), each average being reduced to 100 per cent.

TABLE I

	1	2
SiO <sub>2</sub> .....	52.34	49.06
TiO <sub>2</sub> .....	1.82	1.36
Al <sub>2</sub> O <sub>3</sub> .....	13.70	15.70
Fe <sub>2</sub> O <sub>3</sub> .....	5.05	5.38
FeO.....	8.78	6.37
MnO.....	0.23	0.31
MgO.....	4.72	6.17
CaO.....	8.03	8.95
Na <sub>2</sub> O.....	2.60	3.11
K <sub>2</sub> O.....	1.17	1.52
H <sub>2</sub> O.....	1.56	1.62
P <sub>2</sub> O <sub>5</sub> .....		0.45
	100.00	100.00

Typical basalt, like normal diabase, contains no quartz. The quartz diabases mentioned carry 4 per cent to about 20 per cent of that mineral, and varying proportions of biotite, from zero to perhaps 10 per cent. According to Bowen (p. 46) the quartz and biotite have crystallized because the residual liquid, from which pyroxene, calcic plagioclase, and possibly olivine had settled out, became "enriched in alkaline feldspar molecules and water to give a high concentration and consequent separation of most of those molecules which are formed by the breakdown of the alkaline feldspar molecules (biotite or quartz or both)." But the high content of lime and magnesia in quartz diabase shows the amount of sunken pyroxene, olivine, and plagioclase to be very small. In fact, Collins has illustrated quantitatively the fact that much quartz diabase is essentially normal diabase bearing interstitial

<sup>1</sup> Cf. N. L. Bowen, *Amer. Jour. Sci.*, XXXIX (1915), 178 ff.

micro-pegmatite or myrmekite.<sup>1</sup> On the other hand, quartz diabase is characteristically poorer in alkalis than normal diabase or basalt—a relation just the reverse of that expected on Bowen's hypothesis.<sup>2</sup>

Hence, neither the mineralogical constitution of quartz diabase nor its chemical analyses support the idea that its free quartz is due to fractional crystallization, as postulated.

*Gas-controlled differentiation in the liquid phase.*—That fractional crystallization is only one of several important modes of differentiation is suggested by the activities of magmatic gases. All petrologists recognize the segregation of gas-rich, generally salic, material as magmas complete their crystallization. Assuredly the gases of mobile fractions have been concentrated by the formation of gas-poor, solid crystals. However, one cannot assume a total absence of gas-rich portions in the original magma nor a total inability of resurgent gases to enter the magmatic chamber. If, for these or other reasons, local portions of the magma are or become specially gaseous, these would tend to rise in the chamber and so bring about differentiation independently of crystallization and, it may be, long before crystallization has begun.

The writer has emphasized the possible derivation of augite andesite from basalt by the sinking of crystals. The abundant gas which streams through the vents where augite andesite is generated doubtless lowers the temperature range of consolidation and thereby lengthens the time interval during which crystals may settle. It may also act as a vehicle for the moderate concentration of silica and alkalis in the pipes and thus accelerate the development of a magma contrasted with the original basalt.<sup>3</sup> Lawson expressed a somewhat similar idea in discussing the more salic central parts of the differentiated diabasic dikes around Rainy Lake.<sup>4</sup> This conception does not necessarily imply any degree of immiscibility between the gas-rich and the gas-poor phases of the liquid. It is

<sup>1</sup> W. H. Collins, *Memoir 95, Geol. Surv. Can.*, 1917, p. 96.

<sup>2</sup> See R. A. Daly, *Igneous Rocks and Their Origin* (New York, 1914), p. 321.

<sup>3</sup> Cf. R. A. Daly, *ibid.*, p. 377. That anorthositic differentiation takes place under contrasted conditions is noted on p. 328 of the same book.

<sup>4</sup> A. C. Lawson, *Amer. Geol.*, March, 1891, p. 160.

founded on the slowness of diffusion, a process so sluggish that homogeneity cannot be established or re-established before those phases have been separated by gravity or other forces.

*Question of liquid immiscibility.*—Bowen decides against the hypothesis of liquid immiscibility as a condition for the splitting of silicate fractions. His chief reason is the negative evidence of experimental melts and of glassy lavas; in neither case have immiscible globules been detected, though the artificial or natural quenchings have taken place at all stages in the cooling histories. In spite of such observations, even on melts “in bombs under high pressure of water-vapor,” one cannot but question whether melt or lava flow truly represents the controlling conditions in a great, *quiet*, magma chamber. There, at pressures of hundreds or thousands of atmospheres, the magmatic life is to be measured in weeks, months, years, or centuries. Bridgman’s work indicates the probability of the great undercooling of such a magma by pressure. Kuenen has proved that for some liquids pressure raises the critical temperature of unmixing, for other liquids the reverse.<sup>1</sup> Is immiscibility among silicate solutions developed by undercooling through pressure? Further, are the possibilities of the colloidal state for silicates at continued high pressure sufficiently understood? Until these and kindred problems are solved a definite denial of liquid unmixing in magmas should be postponed.

Bowen’s second reason for rejecting that principle is found in the high melting temperatures of olivine, magnetite, and other components of monomineralic rocks. Temperatures so high cannot be easily, if at all, assumed for most magmas. Yet it is not ascertained that the phase which has separated was pure olivine, magnetite, or any other of the minerals forming the actual monomineralic mass. The temporary dissolving of a very small proportion of hydrogen, oxygen, or water in any of these substances gives the solution a lower temperature of consolidation than that of the corresponding gas-free phase. The writer has long realized the difficulty of crediting all the observed serpentinization of dunites

<sup>1</sup> P. W. Bridgman, *Proc. Amer. Acad. Arts and Sciences*, XLVII (1912), 530; *Physical Review*, III (1914), 182; *ibid.*, VI (1915), 14; J. P. Kuenen, *Phil. Mag.*, VI (1903), 637.

to ordinary weathering or to the action of seepage waters. Possibly much of the alteration is due to magmatic water. Similarly the segregation of the Kiruna magnetite in a liquid phase was perhaps possible because that phase temporarily carried appreciable amounts of oxygen, water, or other gases.

Whatever values these surmises may have, neither the field relations nor the microscopical petrography of a dunite or of the Kiruna magnetite seem to be compatible with the idea that either rock type is a "raft" of accumulated crystals. The writer believes, therefore, that it is wise to keep the hypothesis of liquid unmixing as still one of the competing explanations in these two cases also.

*Failure of sufficient allowance for magmatic assimilation.*—The difficulty of excluding syntexis as a significant general process may be illustrated from a field where Bowen himself has worked. In 1910 he concluded that the granophyre at the roofs of several diabasic sills in the Gowganda district, Ontario, is to be referred to the solution of the invaded sediments.<sup>1</sup> Later he wrote:

This opinion was arrived at principally because of the difficulty of picturing any process of pure differentiation whereby a quartzose rock could be formed from basaltic magma. With this difficulty removed the writer has no hesitation in concluding that the granophyre and the micropegmatite interstices of the diabase were formed after the manner detailed in the present paper [fractional crystallization of pure basalt] and that interchange of material between the granophyre and the adinolized sediment was a subsidiary process contributing to the soda-rich nature of the border phases.<sup>2</sup>

Since 1910 Collins has studied the sills of the same district in detail, proving that granophyric (micropegmatitic or myrmekitic) material has resulted from the interaction of the diabasic magma and the invaded quartzite, etc.<sup>3</sup> Though Collins is conservative in theorizing about the origin of the main granophyric bodies, his evidence agrees with the findings of Bayley, Lawson, and the writer at Pigeon Point, and with the first field impression of Bowen in Collins' field. In view of the close analogy between granophyre and granite the agreement is significant.

<sup>1</sup> N. L. Bowen, *Jour. Geol.*, XVIII (1910), 658.

<sup>2</sup> *Ibid.*, Suppl., XXIII (1915), 49.

<sup>3</sup> W. H. Collins, *op. cit.*, pp. 60, 90. See especially the remarkable photograph in Pl. VIII, A.

*Differentiation a reversible process.*—Tolerance toward the idea of assimilation ought to be specially easy for petrologists who have studied the proofs and processes of differentiation, for differentiation is reversible. This is shown in a variety of ways: First, the original formation of the unstable melt means the former existence of conditions compelling the thorough, mutual solution of all its components. The local re-establishment of those conditions would lead to the re-resolution of phases once separated from the original magma. Secondly, the resorption of phenocrysts is a very common proof of re-resolution and that on a large scale. The crystals forming early in artificial melts are often resorbed before equilibrium is reached. Salt and cold water saturated with salt make a stronger brine at higher temperature. Can hot, primary basalt fail to dissolve some of the heterogeneous substances of the earth's crust with which it makes contact during and after eruption? Thirdly, because the order of eruption is roughly parallel to that of crystallization, and for other reasons, the temperatures of differentiation are to be considered as relatively low. Higher temperature should, then, presumably tend to restore homogeneity. Finally, the solution of older gabbro in the red-rock magmas, shown at Pigeon Point, Duluth, near Nordingrå, and elsewhere, proves the ability of even a late differentiate to make a new mutual solution with solid rock of essentially the same kind as that now representing the other pole of its own differentiation.<sup>1</sup>

If, then, magmatic differentiation is reversible, assimilation of foreign, solid rocks is seen to be all the more probable. The case of the red rock and gabbro shows that very high temperature may not be necessary for solution; concentration of water is another of the important factors.

Space cannot here be taken for a statement of the many facts (e.g., replacement of invaded formations by batholithic rocks) directly supporting the assimilation theory. They are amply competent to forbid belief that fractional crystallization is the only important cause for the diversity of igneous rocks. Some revision of the subject is called for when Bowen (p. 90) remarks that the

<sup>1</sup> R. A. Daly, *Amer. Jour. Sci.*, XLIII (1917), 442 (footnote); A. G. Högbom, *Geol. Fören. Stockholm Förhand.*, XXXI (1909), 368.

reasons for assuming assimilation on an appreciable scale "are considered to be *entirely* removed when it is shown that the types enumerated above and probably all other igneous rocks *could* be derived from basaltic magma by differentiation alone." A lapse of logic is indicated by the italicized words.

*Hybrid rock not the normal result of assimilation.*—One must doubt that the "formation of an obviously hybrid rock" should be the "normal result of assimilation" (Bowen, p. 85). A fused xenolith or the solute slowly diffusing away from its source into the dissolving magma tends, as already noted, to rise (or sink) in the general body of liquid. As the foreign material moves under gravity it is more and more mixed with the original magma. This more dilute solution, retaining nearly all of its original temperature, is about as likely to separate as any part of the original magma itself. The special composition of the absorbed rock may of itself stimulate strong differentiation. Under the conditions hybridism is far from being obvious.

The lowering of crystallization temperature by mixture may have little to do with the differentiation of many syntectics. Back of all theorizing are two fundamental questions: How greatly is primary, dissolving magma superheated? What is the ratio of its volume to that of its solute? In other words, how much work is supposed to have been done and what was the amount of energy available?

The petrologist should think always to scale, in space!

*Meaning of chilled contacts in batholiths.*—Bowen states (p. 84) that little assimilation can be admitted in the case where a batholith has a chilled contact against its country rock. If stoping established the visible contact, the magma was nearly frozen; for, if it had been very hot, further stoping would have occurred. The visible contact was made after the sinking away of the last batch of shattered blocks from the main country rock. The chilling effect is thus due to the relatively low temperature of the new, last surface of contact made with the invaded formation. In that case the chilling phenomena give no trustworthy indication of the assimilating power of the batholith during its enormously long magmatic life.

The petrologist should think always to scale, in time!

*Loci of magmatic assimilation.*—Again, the importance of batholithic assimilation is to be properly gauged only if all its different loci are kept in mind. In part it is marginal, affecting the roof region and also the vast walls, independently hot, at great depth. For the rest it consists of the fusion or solution of xenoliths, either near the roof or at deep levels. Accordingly batholithic assimilation may be described as:

1. Marginal: (a) High-level, (b) Abyssal.
2. Xenolithic: (a) High-level, (b) Abyssal.

Of the four kinds the xenolithic-abyssal and the marginal-abyssal are probably most important. Yet precisely these loci of the geological work, typically very deep, can seldom or never be exposed to view by erosion. Hence batholithic syntaxis, beside which all other is an almost vanishing quantity, can be inferred only from its results. Its whole meaning for petrology is not to be directly deduced from visible contacts.

*Bowen's special suggestions as to the origin of alkaline types.*—The foregoing considerations are vital in the theory of alkaline rocks, but Bowen's petrogenic scheme raises doubts when some of his more specific points are examined. He recognizes two principal modes of origin for the alkaline rocks, as stated in the following quotations from his memoir (pp. 56, 57):

It has been shown that at the biotite granite stage [of evolving basaltic magma], and to a lesser extent in preceding stages, reactions take place in the liquid whose principal feature is the breakdown of polysilicate molecules, probably under the influence of water, to the simpler orthosilicate molecules, among them  $\text{KAlSiO}_4$  and  $\text{NaAlSiO}_4$ . The precipitation of  $\text{KAlSi}_3\text{O}_8$ ,  $\text{NaAlSi}_3\text{O}_8$ ,  $\text{KAlSiO}_4$  in mica, and  $\text{SiO}_2$  as quartz means the concentration in the liquid of all the other molecules indicated in the reactions given on pp. 44 and 45. These are principally  $\text{NaAlSiO}_4$  and the volatile constituents, water, chlorine, etc., with their compounds. If the crystals of the biotite granite stage, including quartz, sink out of this liquid, then the concentration of  $\text{NaAlSiO}_4$  will finally reach a stage where nephelite will begin to precipitate. There may also result a concentration of  $\text{CO}_2$ , S,  $\text{SO}_3$ , Cl, etc., sufficient to cause their precipitation in compounds such as cancrinite, lazurite, hauynite, and sodalite, minerals which are peculiar to nephelite syenites and related rocks. . . .

Differentiation during crystallization from these very fluid [alkaline] magmas will take place very freely, and the formation of both highly femic and highly alkalic types (rich in feldspathoids) may result. The more "basic"



types of alkaline rocks are not, however, in all cases basic differentiates from nephelite syenite magma. The reactions preliminary to the separation of quartz and biotite begin at an early stage in the crystallization of basaltic magma, and the separation of these minerals may take place at an early stage, giving rise to quartz diorites or granodiorites. The possibility of the formation of alkalic magma at a stage much earlier than the biotite granite stage is thereby introduced if conditions are favorable. Favorable conditions seem to consist in the opportunity for sinking, not only of the plagioclase crystals and femic minerals, but also of the quartz crystals in sufficient amount. Thus may result relatively "basic" alkaline magmas from which such rocks as basanite might be formed, and nephelite syenite itself as a light differentiate.

*Assumed desilication by the settling-out of quartz crystals.*—The evolution of feldspathoid-bearing magma from the biotite-granite stage is supposed to be accomplished by the separation of crystals of orthoclase, albite, mica, and quartz. A critical element is the actual removal of quartz, and the doubtful nature of this assumption affects the whole argument. In frozen granite, whether a part of a large batholith or wholly constituting a more quickly chilled sill or dike, the quartz is all, or nearly all, interstitial. In the typical case there is no evidence that the quartz crystallized early, so as to be capable of settling-out. Rhyolites do bear phenocrystic quartz, but probably for special reasons. It would be wrong to regard rhyolites as exact homologues to granite in mode of crystallization. In any case the groundmass of rhyolite or quartz porphyry is itself very rich in free silica, and it is difficult to imagine how the groundmass quartz could be removed so as to leave a quartz-free residuum like nephelite syenite.

The same trouble arises in connection with the second postulated method of development, namely, from quartz-diorite or granodiorite magma. The quartz of quartz-diorite and granodiorite is again interstitial and seldom shows any tendency to phenocrystic relations.

*Origin of basanite.*—Can basanite be derived by the sinking of quartz and other minerals from evolving basalt? Solid basanite has a specific gravity near 2.95. In the liquid state its specific gravity would be about 2.60, a value little if any greater than that of the magma in the immediately preceding stage. On the other hand, the quartz crystals at the temperature of this magma would

have a specific gravity of about 2.54. Obviously the assumption that they would sink at all needs further justification.

The hypothesis concerned faces objections on chemical grounds. Table II gives the average of the analyses of 20 typical basanites (col. 1) and the corresponding averages for 20 quartz diorites (col. 2) and 12 granodiorites (col. 3).

TABLE II

	1	2	3
SiO <sub>2</sub> .....	44.41	59.47	65.10
TiO <sub>2</sub> .....	1.56	0.64	0.54
Al <sub>2</sub> O <sub>3</sub> .....	15.81	16.52	15.82
Fe <sub>2</sub> O <sub>3</sub> .....	4.66	2.63	1.64
FeO.....	5.85	4.11	2.66
MnO.....	0.14	0.08	0.05
MgO.....	8.20	3.75	2.17
CaO.....	10.12	6.24	4.66
Na <sub>2</sub> O.....	3.81	2.98	3.82
K <sub>2</sub> O.....	2.37	1.93	2.29
H <sub>2</sub> O.....	2.42	1.39	1.09
P <sub>2</sub> O <sub>5</sub> .....	0.65	0.26	0.16
	100.00	100.00	100.00

Inspection of the table shows that the settling-out of "plagioclase crystals and femic minerals" as well as quartz could not produce a basanitic magma from that of either quartz diorite or granodiorite. For instance, the potash should be much higher in the basanite unless it be assumed that much biotite had settled out; but if it had, the iron oxides and magnesia should be proportionately diminished. Yet these components of the femic minerals are much more abundant than in either of the postulated parent magmas. Nor is it likely that the lime could be relatively so much increased in the mother-liquor after the manner suggested, that is, by the sinking (or rising) of plagioclase crystals and femic crystals.

*Absence of foyaitic types in most batholiths and stocks.*—Again the theory suffers statistically as regards the occurrence of alkaline rocks. If, as Bowen holds, the cooling of a great body of granite magma should normally generate a foyaitic submagma as an end product, then all or most granite batholiths and most of the largest stocks should exhibit foyaitic phases. They do not.

*Absence of quartz-bearing lavas in many basalt-trachyte-phonolite volcanoes.*—Similarly phonolite should emanate from most old, large volcanoes. Quartzose lavas (quenched, interim phases) should be commonly found in the oceanic volcanoes which are built of phonolite or trachyte and basalt. These expectations also do not agree with the facts.

*Eruptive sequence.*—In view of the great complexity of the problem not too much stress should be laid on special cases, but it is well to point out a questionable argument relating to the eruptive sequence. Bowen implies (p. 64) that the nephelite syenite-malignite member of the Okanagan composite batholith has its theoretically correct time relation to the other members. On the contrary, the alkaline body is distinctly older than the Similkameen granite batholith, and not younger, as would be naturally expected if the alkaline mass represents the residual liquor of the granite as it crystallized. The neighboring, intensely sheared Osoyoos granodiorite is very much older than the unsheared alkalines, and any direct genetic bond between these two is improbable.

More generally, the writer cannot believe that the world's eruptive sequences support the thesis that foyaïtes, phonolites, trachytes, etc., are simply the products of the fractionation of pure basalt.

*Comparison of basalt and femic, feldspathoid-bearing types.*—A formidable array of difficulties with that explanation appears when average basalt (see col. 1 of Table III) is compared chemically with the more femic members of the alkaline suite, such as average nephelite basalt (col. 2), analcite basalt from the Highwood Mountains (col. 3), average leucite basalt (col. 4), average leucite basanite (col. 5), and average theralite (col. 6).<sup>1</sup>

The high lime, magnesia, and iron oxides in cols. 2 to 6 inclusive cannot be reconciled with the hypothesis that the relatively high soda or potash has been developed by the removal of olivine, pyroxene, or calcic plagioclase, or any combination of them, out of an average or typical basaltic magma. The lime content of

<sup>1</sup> Cf. Table II in the writer's *Igneous Rocks and Their Origin*, 1914; and L. V. Pirsson, *op. cit.*, p. 173.

cols. 2, 4, and 5 and the high magnesia of col. 2 are specially noteworthy. On the other hand, this hypothesis does not explain the dominance of potash over soda in cols. 4 and 5, nor the abundant water in the analcite basalt.

TABLE III

	1	2	3	4	5	6
SiO <sub>2</sub> .....	49.06	39.87	47.82	46.47	45.34	45.61
TiO <sub>2</sub> .....	1.36	1.50	0.67	1.33	1.30	1.96
Al <sub>2</sub> O <sub>3</sub> .....	15.70	13.58	13.56	15.97	16.59	14.35
Fe <sub>2</sub> O <sub>3</sub> .....	5.38	6.71	4.73	5.97	5.83	6.17
FeO.....	6.37	6.43	4.54	4.27	4.76	4.03
MnO.....	0.31	0.21	tr.	0.01	0.01	0.19
MgO.....	6.17	10.46	7.49	5.87	5.43	6.05
CaO.....	8.95	12.36	8.91	10.54	11.64	9.49
Na <sub>2</sub> O.....	3.11	3.85	4.37	1.69	2.93	5.12
K <sub>2</sub> O.....	1.52	1.87	3.23	4.83	4.55	3.69
H <sub>2</sub> O.....	1.62	2.22*	3.37	2.32	1.12	2.60
P <sub>2</sub> O <sub>5</sub> .....	0.45	0.94	1.10	0.73	0.50	0.74
	100.00	100.00	99.79	100.00	100.00	100.00

\*Includes 0.29 per cent CO<sub>2</sub>.

Perhaps fuller statement of the hypothesis might annul some of the writer's doubts which have been raised by these and other fundamental facts of magmatic differentiation, but at present he fails to see that the mechanism works as it should if the pure-fractionation theory were correct.

*Admission of some assimilation by magmas.*—Bowen states (pp. 84, 89):

As a matter of fact, plain evidence is found in the field that magmas do assimilate, especially when they occur in the large bodies commonly termed batholiths. . . . It may well be, also, that some melilite rocks are formed by the crystallization of a syntectic magma formed by the solution of limestone. . . . If the absorption of any considerable amount of limestone by a magma can be admitted, it may be expected to have a very unusual effect upon the magma. . . . The taking of silica from feldspar molecules by the lime and the consequent production of feldspathoid molecules might well be supposed a reasonable possibility. Some alkaline rocks may, perhaps, be so generated.

Yet Bowen believes "that normally the alkaline rocks enter into an eruptive sequence as the products of differentiation solely."

Only a very small addition of foreign lime (1 to 10 per cent) to a large mass of basaltic magma would be necessary to produce

the total amount of desilication observed in any nephelitic or leucitic body yet discovered. Considering the fluxing power of limestone or dolomite on silicate melts, such moderate, local assimilation is surely not improbable. More siliceous sediments or even gneissic or granitic rocks may be simultaneously dissolved; but, on account of its character as a flux, a carbonate rock is likely to be absorbed in greater volume. Hence it does not follow that the solution of "an occasional bed of limestone in a terrane consisting principally of siliceous gneisses . . . would entail simultaneous absorption of a much greater quantity of relatively siliceous material" (Bowen, p. 63). The relative amounts absorbed must really depend on a number of factors, including the contact relations of each layer of the country rocks to the invading magma.

*Meaning of melilitic rocks.*—Bowen's admission regarding the melilite rocks is of particular significance when one remembers the exceeding intimacy of alkali-rich rocks with melilite basalt, nephelite-melilite basalt, and alnöite.<sup>1</sup>

*Résumé.*—The prominent difficulties with Bowen's theory may now be summarized.

The sinking or rising of crystals in magmas is a true cause of diversity in igneous rocks, but it is not the only important cause; perhaps it is much less important than the separation of liquid phases. Apart from the possible development of "liquid immiscibility" in an initially homogeneous magma, separation in the liquid phase is to be expected: (1) if the magma at the time of emplacement in a large chamber were heterogeneous; (2) if for any reason gases are concentrated locally within the magmatic body; and (3) if the assimilation of country rocks, or of their volatile constituents alone, takes place. The field evidences for important assimilation are not consonant with the pure-fractionation theory.

Bowen's theory seems to imply a greater facility of differentiation for basaltic and other magmas than they actually possess; most sills and laccoliths are not visibly differentiated, even though they show features implying fluency after injection. The theory gives no good explanation of the comparatively abrupt transition

<sup>1</sup> See the writer's *Igneous Rocks and Their Origin*, p. 436, and Appendix D.

between the syenite and shonkinite of the Square Butte laccolith, nor of the apparent homogeneity of that shonkinite. It fails to take account of the lack of ultra-femic phases in the Pigeon Point and other sills which display notable salic differentiates. Its consequence, that all monomineralic rocks except certain sulphides are crystal "rafts," may fit the case of anorthosite, but not other cases. Other special objections are found in the chemical nature of quartz diabase, basanite, and the "alkaline basalts." The absence of foyaitic phases in, or apophysal from, most large bodies of granite, granodiorite, and quartz diorite does not agree with the theory as developed. Similarly quartzose lavas, expected on the theory, are not found in many volcanic piles containing trachyte or phonolite with basalt. The lack of quartzose lavas in the enormous and therefore long-lived volcanoes distributed over the main ocean floor is a fact not easily explained by the theory.

Bowen has given the clearest, most detailed argument for the significance of fractional crystallization which has yet been published. His general theory takes cognizance of: the proved genetic association of alkaline rocks with subalkaline magmas, especially the basaltic; the small size of alkaline bodies; their richness in gases and rare elements; the consequent effects regarding grain and variability of composition; the roof positions of alkaline differentiates in many sills, laccoliths, and batholiths; and the concentration of alkalies. Nevertheless, all of these facts are explicable also on the syntectic-differentiation hypothesis, which does not encounter certain difficulties facing the theory of pure fractional crystallization.

#### GENERAL CONCLUSION

Thus the study of the geological publications issued since the completion of the manuscript of the writer's *Igneous Rocks and Their Origin* has led him to renewed faith in the general explanation there advanced for most of the alkaline rocks. Several expert field observers have sympathetically entertained the hypothesis of control by the syntexis of basic sediments charged with volatile matter. Evidence for the derivation of alkaline rocks from subalkaline magmas has been still further accumulated. Some authors have expressed a degree of confidence that basalt is the only primary

magma eruptible since the end of pre-Cambrian time. Foye has made an extraordinarily important contribution in showing the vast quantity of alkaline solutions which may emanate from granite invading a limestone terrane. Like Allan he has given new, good evidence of the influence of gravity in the separation of magmatic phases. Foye corroborates the decision of Adams and Barlow as to the syntexis of limestone and granite in a complex now famous for its nephelite syenites. Quensel's discovery of an analogy to Alnö in the Almunge district and of the peculiar abundance of vesuvianite in the Almunge canadite is likewise to be particularly recorded. The arguments presented by Cross, Marshall, Richards, and others against the sediment-syntectic explanation of the alkaline rocks are seen to be inconclusive.

Shand finds the syntexis of limestone a partial explanation of undersaturation in igneous rocks. Smyth's view concerning the alkaline series is not acceptable, on the ground that he fails to show cause for the local and exceptional assembling of alkaline elements from subalkaline magmas, assumed by him to be purely juvenile. Experiments by Ross and other students of the commercial-potash problem show the power of lime to volatilize the alkalies from feldspathic or clay mixtures, even at comparatively low temperature.

Certain aspects of Bowen's comprehensive theory have been studied. Serious doubt adheres to some of his fundamental postulates, summoned to explain the descent of alkali-rich rocks from subalkaline magma. On the other hand, many features of his excellent paper must receive hearty commendation from all thinking petrologists; in masterly fashion he has indicated many new, important lines of thought and research.